The golden colored blackening waxcap *Hygrocybe conica var. aurantiolutea* is a colorful member of waxcaps that grows in grasslands in the low and sub-Arctic zones. At appropriate climatic conditions, the cryptically growing long-lived mycelia produce sporocarps in August-September. Waxcaps are sensitive to nitrogen, and their occurrence is strongly reduced in temperate and boreal zones due to anthropogenic deposition of nitrogen and fertilization. Tasiusaq at Qassiarsuk in South Greenland, 1987. Photo: Flemming Rune.
I want to tell you something I learned about plants from the late Kakkik that I tried myself. My sister’s late husband used to know about nírnait, caribou lichen, the plants that caribou eat. They are long and you pull them out. They tend to grow in swampy areas. I boiled them when all the people in our camp were sick. I was the only one up and about when we were living in a fishing camp. My mother had been admitted to the hospital and we were waiting for her return in August. Six of my family members were sick in bed. I boiled some caribou lichen in a pot for a long time, following my brother-in-law’s advice. He told me to stop boiling them when the water turned black. I waited for them to cool down and I gave each sick person some to drink. The next day, they were all up and about. It looked like the cough syrup in a bottle.

SUMMARY

Fungi are one of the most species-rich groups of organisms in the Arctic. While the occurrence, distribution and ecology for lichenized fungi (lichens)\(^1\) are reasonably well known, less is known about non-lichenized fungi (normally just called fungi), including lichenicolous fungi (fungi living on lichens)\(^2\) and in particular, microfungi\(^3\). The known number of fungal species in the Arctic is presently about 4,350, of which 2,600 are macrofungi\(^4\) and 1,750 are lichens, the rest are microfungi. The fungi have largely a cryptic life form and have therefore not been exhaustively inventoried. Hence, total fungal-species richness in the Arctic may exceed 13,000. Local species richness is typically high and can be very high, e.g. about 50 lichen species on less than 1 m\(^2\). Most species appear to be present throughout the Arctic, and they also occur in alpine habitats outside the Arctic, particularly in the northern hemisphere. Few fungi are endemic to the Arctic. Of the lichens, 143 species are listed as Arctic endemics, but it is likely that the major part will prove to be synonyms of other species.

Fungi are pivotal in Arctic terrestrial food-webs. Mycorrhizal, saprotrophic\(^5\) and pathogenic fungi drive nutrient and energy cycling, and lichens are important for primary production. Reindeer lichens Cladonia subgenus Cladina spp. form dominant vegetation types in many areas and function as keystone species.

As for other inconspicuous organism groups, it is obviously desirable to gain a better knowledge of the identity, occurrence and functions of fungal species, and particularly the large number of unrecorded species (mainly microfungi). An evaluation of the conservation status of Arctic fungi is feasible, and the mapping of rare and endemic species is necessary. Enhanced monitoring and functional research would enable more accurate prediction of how fungal diversity and the ecosystem functions of fungi will develop with climate change.

Effects of climate change on diversity of Arctic fungi are predicted to be gradual but radical over time, due to changes in vascular plant flora and vegetation, especially the expansion of shrubs. Most fungal species associate with living or dead parts of specific vascular plants and will respond directly to changing composition, abundance and location of the vegetation. Similarly, terricolous\(^6\) lichen communities will be affected by increased competition from vascular plants. The changing vegetation will transform the fungal diversity and thereby affect ecosystem services provided by fungi, such as plant’s uptake of nutrients, decomposition and long-term carbon sequestration in soil, although unknown how and to what degree. The conservation status of Arctic fungi is predicted to scarcely be affected within the next decades but greatly changed over the long term.

10.1. INTRODUCTION

Fungi are an extraordinary group of organisms. They constitute a large portion of Arctic biodiversity and are essential in the functioning of Arctic terrestrial ecosystems. A substantial part of the fungi is lichenized and generally termed lichens. The remaining part of the fungi is in general terms just called fungi and will here be referred to as fungi. Given favorable weather conditions, some may produce short-lived, sometimes prominent, sporocarps (mushrooms), but predominantly, and for many species exclusively, they exist as cryptic and hidden mycelia in e.g. soil and in living or dead insect or plant tissues. The most well-known group of fungi in the Arctic is the lichenized fungi (lichens) because they grow on substrate surfaces and often contribute conspicuously, and colorfully, to Arctic vegetation. This is particularly apparent in the high Arctic and in reindeer lichen\(^7\)-dominated vegetation types in the sub-Arctic.

Here we review the knowledge and status of Arctic macroscopic fungi, i.e. visible sporocarps of fungi, and lichens. Microfungi constitute the most species-rich fungal group in the Arctic, but are only briefly mentioned due to scarcity of knowledge.

10.2. STATUS OF KNOWLEDGE

10.2.1. Fungal life strategies and ecosystem functions

Fungi are heterotrophic, i.e. they cannot fix carbon but need organic carbon for growth and therefore rely on photosynthetically derived energy from plants, including algae and cyanobacteria. Their strategies to access this energy are to be (1) mutualistic\(^8\) (i.e. to associate

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\(^1\) Lichenized fungi live in symbiosis with photosynthetic green algae or cyanobacteria and form stable structures called lichens.

\(^2\) Lichenicolous fungi live exclusively on lichens, commonly as host-specific parasites, but also as broad-spectrum pathogens, saprotrophs or commensals.

\(^3\) Microfungi are defined as fungi either lacking known reproductive structures, with microscopic reproductive structures or small sporocarps, typically less than 2 mm. They constitute the majority of known species and likely the overwhelming majority of the yet unknown and undescribed fungi.

\(^4\) Macrofungi are defined as fungi with visible, sporocarps, typically larger than 2 mm.

\(^5\) Saprotrophic organisms decompose dead plant, animal or fungal tissues.

\(^6\) Organisms living on or in the soil.

\(^7\) Despite being lichens, reindeer lichens are sometimes called “reindeer or caribou moss”.

\(^8\) Mutualism is a relationship between two species of organisms in which both benefit from the association, e.g. fungi and plants in mycorrhizae and fungi and green algae or cyanobacteria in lichens.
with photosynthetic organisms), (2) endophytic, (3) saprotrophic (i.e. they decompose dead plant, animal or fungal tissues) or (4) parasitic.

Fungal mutualism may be in the form of lichen or mycorrhiza. Lichens are an intimate, long-lived and stable association between fungi and green algae and/or cyanobacteria. Each lichen species has a unique fungus or mycobiont that determines its appearance and properties as well as its taxonomy, while the photosynthetic symbionts (photobionts) consist of relatively few species (148 according to Voytsekhovich et al. 2011), which are globally widespread and sometimes free living (Nash 2008). Lichens are classified and named after their fungal symbionts. The majority of Arctic vascular plants species form different types of mycorrhizae (Gardes & Dahlberg 1996, Newsham et al. 2009). The complex mycorrhizal organ, consisting of plant root and fungal hyphae, enlarge the surface area for absorbing water and nutrients from soil, explore for nutrients more extensively than vascular-plant roots, and mobilize organically bound nutrients. The fungal association provides the fungus direct access to the plant’s carbohydrates, while the plant gain benefits from improved mineral and water absorption through the fungal mycelium. Ectomycorrhizal fungi are common in the Arctic where they associate with roots of mountain avens Dryas spp., willows Salix spp., birch Betula spp. and alpine bistort Bistorta spp. and in the sub-Arctic with additional species of bushes and trees. Ectomycorrhizal fungi belong mostly to genera forming conspicuous sporocarps, e.g. boletes (e.g. Leccinum spp.), amanitas Amanita spp. and milk-caps Lactarius spp. Arbuscular mycorrhizae are widespread in Arctic species of the true grasses Poaceae, the buttercup family Ranunculaceae, the aster family Asteraceae, the saxifrage family Saxifragaceae and the rose family Rosaceae (e.g. Gardes & Dahlberg 1996, Olsson et al. 2004, Ormsby et al. 2007, Peters et al. 2010, Walker et al. 2010). Ericoid mycorrhizae are widespread in Arctic species of the heather family Ericaceae, e.g. huckleberry Vaccinium spp., bell-heather Cassiope spp. and crowberry Empetrum spp. (Walker et al. 2011). The fungal symbionts in arbuscular and ericoid mycorrhizae are microfungi and typically need microscopic root examination to be seen, or molecular tools to be detected and identified.

The few studies conducted of Arctic fungal endophytes indicate a high species diversity, e.g. in above ground tissues of mountain avens (Higgins et al. 2007) and associated with Arctic plant roots, as so called dark septate endophytes (Newsham et al. 2009). Recently, fungal endophytes have been found common in lichen thalli (Arnold et al. 2009, U’ren et al. 2010).

Saprotrophic fungi are characterized by their dependence on dead organic materials as sources of energy and nutrients. They consist predominantly of microfungi, including a large number of anamorphic (asexual) ascomycetes and yeasts but also macrofungi (Ludley & Robinson 2008). Hitherto, the information on microfungi has largely been restricted to culturable mycelia from soil and plants (Ludley & Robinson 2008). Molecular tools are now providing exciting opportunities to resolve the diversity, distribution and function of fungal mycelia in the Arctic. The saprotrophic macrofungi producing larger sporocarps include puffballs Calvatia, funnels Clitocybe, Galerina and Leptoglossum. Pyrenomycetes is a common group of saprophytic microfungi mostly apparent as black dots on dead plants that are frequent in the Arctic (Lind 1934, Savile 1963).

Fungal parasites are normally specialized microfungi attacking plants, animals, in particular invertebrates, and sometimes also fungi. They may have large effects on the population sizes of their hosts, but have not been extensively studied in the Arctic (but see Savile 1963). Examples of Arctic parasites are rust fungi such as Melampsora that commonly cause mortality of willows (Parmelee 1989, Smith et al. 2004) and smuts (Ustilaginales), parasitizing plants of Cyperaceae (Scholler et al. 2003). Another group of frequent pathogens in the Arctic are the snow molds that attack mosses and vascular plants under snow-cover when plant resistance is lowered (Tojo & Newsham 2012).

Fungi are pivotal for the cycling of carbon and nutrients (including N) in terrestrial ecosystems of the Arctic (Ludley & Robinson 2008, Newsham et al. 2009). Until recently, in ecological studies fungi were lumped with other microbes into a ‘black box’, and both the identity and roles of fungi in Arctic regions were largely unknown (Callaghan et al. 2004). The majority of Arctic plants’ nutrient uptake is accomplished by mycorrhizal symbioses. Lichens are significant primary producers in the Arctic, and their contribution of biomass ranges from 2% in low Arctic to over 18% in high Arctic tundra and 65% in polar desert habitats (Webber 1974, Longton 1988). The proportion of Arctic vegetation biomass associated with mycorrhizal fungi has been estimated to range from 17% to 100% (Olsson et al. 2004). The cyanobacterial photobionts of Arctic lichens contribute significantly to nitrogen fixation (Crittenden & Kershaw 1978). Note that while the fungal part in lichens constitutes the major part of the lichen biomass, the mycorrhizal fungi constitute only a minute part of the plant biomass.

The decomposition of dead organic matter and recycling of nutrients in Arctic terrestrial systems is mainly conducted by saprotrophic fungi, with contributions by mycorrhizal fungi, and to a lesser degree by bacteria (Ludley & Robinson 2008, McMahon et al. 2009). Fungi have a major advantage over bacteria in this regard due to their ability to redistribute nutrients and carbohydrates within their extended hyphae and thereby overcome spatial deficiencies.

The presence and diversity of fungal species is largely determined by the distribution, diversity and abundance
of vascular plants and for lichenicolous fungi\(^{10}\) of the lichens. Fungi parasitizing insects rely on the occurrence of their host animals. Some fungal species are confined to a single plant species, whereas others may associate with a few or several plant species. The majority of Arctic lichenicolous fungi are confined to one lichen genus (Zhurbenko 2010a). On the other hand, common Arctic lichen species or genera may host many lichenicolous fungi (e.g. about 20 on Stereocaulon spp. or Thamnolia spp.; Zhurbenko 2010b, 2012). Lichens ecologically resemble bryophytes. Their distribution depends primarily on habitat conditions (e.g. substrate type: rock-soil-bark, pH, microclimate, etc.) and competition by other plant species.

10 Lichenicolous fungi constitute a functional non-taxonomic group of mainly ascomycetes and rarely basidiomycetes or other groups that forms obligate associations with lichens, as commensals, parasites or rarely saprotrophs. They are typically included in lichen checklists. Infection of lichens is typically considered as commensal or parasitic (Fahselt et al. 1989).

### 10.2.2. Fungal properties and adaptations to Arctic conditions

The short growing season and restricted opportunities for reproduction in the Arctic is thought to have selected for high longevity in individual fungi, slower population growth, and hence lower turnover than in more productive biomes (cf. Gardes & Dahlberg 1996). Local spreading relies primarily on mycelial growth or asexual spores rather than sexual reproduction. Population dynamics of fungi have not been studied in the Arctic, but may be inferred from boreal and temperate biomes (cf. Dahlberg & Mueller 2011). There, soil-inhabiting fungal genotypes may potentially, in stable conditions, exist for centuries, or even longer as mycelia. Furthermore, patterns of sporocarp fairy rings and molecular studies reveal that genotypes of mycorrhizal and other soil-dwelling macrofungi typically extend from a few to several hundred square meters. In contrast, substrate-bound saprotrophic and pathogenic fungi are restricted in age and space. However, they may also disperse by asexual spores and sometimes as mycelia by insects, enabling genotypes to spread and persist longer than their host substrates.

Many lichen genotypes can most easily disperse by thallus fragmentation, and subsequently be transported by wind, water or animals over considerable distances. Some lichens even have specialized organs for fragmentation composed of fungal hyphae and algal cells, i.e. isidia, small thallus outgrowths that easily break off, or soredia, smaller powdery propagules. Hence, whereas single genotypes are localized in soil-dwelling fungi, they are typically more scattered and dispersed in lichens (e.g. Scheidegger & Werth 2009, Geml et al. 2010). Significant genetic differentiation at the landscape level has been shown in two Arctic lichens, a crustose Porpidia and a fruticose reindeer lichen, Cladonia arbuscula (Werth 2010). Most Arctic rock-dwelling crustose lichens reproduce sexually and are dispersed by spores (Fahselt et al. 1989).

Analyzing the increment of thallus radius over time (Rhizocarpon geographicum is frequently used in lichenometry), large thalli of rock-dwelling crustose lichens have been estimated to be up to several thousands years old (Matthews & Trenbirth 2011). These estimations are based on circumstantial evidence and linear extrapolation of growth rates derived from data for several decades or a few centuries. It is possible that exceptionally large crustose lichen thalli may be formed by the coalescence of neighbouring thalli rather than by slow radial growth and are not genetic ‘individuals’, though this is not probable for R. geographicum (e.g. Clayden 1997). Similar estimates of potential longevity of reindeer lichen genotypes are not possible, as the older portions at the base of thalli decay after about 30 years (Holt & Bench 2008). The annual growth of Arctic-alpine lichen thalli is seldom expressed as a change in surface area, thickness or biomass. Usually, it is measured and reported as a radial change that ranges from 0-0.5 mm per year in some crustose species (e.g. R. geographicum) to about 6 mm per year in reindeer lichens (Pegau 1968, Werner 1990, Armstrong & Bradwell 2010, Matthews & Trenbirth 2011, Bültmann & Daniëls 2012).

Arctic fungi have evolved physiological mechanisms to maintain mycelial activity and growth at low temperatures and low water potential (Robinson 2001). Even when soils are frozen, microbial processes in the Arctic continue. Fungi contribute 10 times more to Arctic soil microbial biomass than cohabiting bacteria. Microbial processes, i.e. predominantly of fungal origin, reach their annual peak under snow (e.g. Schadt et al. 2003), take up carbon from the environment and grow in frozen soils at least down to -2 °C (McMahon et al. 2009). Arctic lichens may have a positive net primary photosynthesis balance at low temperatures (many studies by K.A. Kershaw and co-workers, e.g. Larson & Kershaw 1975, Kershaw 1985), even under snow and ice, and survive extremely low temperatures and levels of water content (Kappen et al. 1996, Sommerkorn 2000).

Arctic and alpine ectomycorrhizal mushrooms species have evolved substantially smaller sporocarps and a reduced number of gills compared with their forest counterparts, probably as a response to restricted assimilate accessibility and the dry, harsh environmental conditions (Knudsen 2006). Similarly, sporocarps of many microfungi (observed in the pyrenomycete group) tend to be smaller in the Arctic (Savile 1963). The short growing season has also pushed parasitic species of Arctic rust and smuts to have simplified lifecycles, e.g. perennial habits which enable growth as soon as the season starts (Lind 1927, Savile 1982). Finally, lichenization is relatively more common in Arctic than in temperate areas. For example, the number of lichens vs. the number of macrofungi is about 1:1 in Greenland and 1:2 in Great Britain (Knudsen 2006), and the percentage of lichenized
fungi of all known fungi is about 20% at the global level and 35% for the Russian Arctic (Zhurbenko 2010a).

10.2.3. Historic and present investigations

The first overviews of Arctic fungi were published for Svalbard by Karsten (1872) and for Greenland by Rostrup (1888) (for an extensive overview, see Elvebakk & Prestrud 1996, Gulden & Torkelsen 1996, Knudsen 2006). A brief history of the early mycology in the Canadian Arctic is presented by Savile (1962). Due to the ephemeral and irregular occurrence of sporocarps combined with the low accessibility for humans to the Arctic, macrofungi are collected with considerably less frequency than lichens, and hence the knowledge of their distribution and ecology is correspondingly lower. Regional species lists are available for Greenland, Iceland, Svalbard and the Russian Arctic, but a combined checklist for Arctic fungi has not yet been compiled (Elvebakk & Prestrud 1996, Karatygin et al. 1999, Hallgrimsson & Eyjólfsdóttir 2004, Borgen et al. 2006, Hallgrimsson 2010). Unfortunately, regional lists cannot easily be combined because of varying taxonomy. Therefore, knowledge of macrofungal distribution is presented at the level of Arctic Russia, Greenland and Svalbard. Iceland is also considered, although most of that country is classified as sub-Arctic. The Russian Arctic fungal checklist also includes species from the sub-Arctic and reports the recorded species numbers in the Arctic proper to be 20-30% less than when the sub-Arctic is included (Karatygin et al. 1999). No comprehensive checklist exists for the main North American Arctic, although the distributions of some Arctic species in Canada are reported by Redhead (1988). Arctic species tend to have wide distributions, more or less throughout the Arctic (experiences by authors and e.g. Lind 1934, Cripps & Horak 2006, 2010, Ronkier & Ronkier 2010).

Information on fungal specimens in Arctic herbaria is increasingly accessible through the global biodiversity information facility, GBIF (2012), but is still very incomplete. To promote the development of Arctic and alpine mycological knowledge, mycologists have cooperated in the International Symposium of Arcto-alpine Mycology network (ISAM) since 1980 and have arranged nine symposia with more than 100 participants in total and almost 100 scientific papers presented (Laursen & Ammirati 1982, Laursen et al. 1987, Petriń & Laursen 1993, Mukhin & Knudsen 1998, Boertmann & Knudsen 2006, Høiland & Økland 2008, Cripps & Ammirati 2010).

By necessity, Arctic mycological research has been primarily exploratory, focusing on identification, description and recording of fungal taxa. Few analyses of patterns and dynamics of macrofungal communities and of Arctic fungal ecology have been made (e.g. Lange 1957, Petersen 1977). Recent advancements in molecular approaches enable the detection, genetic characterization and quantification of fungi in environmental samples, e.g. soil and plant tissues. These data will significantly help to increase knowledge of Arctic mycology by complementing studies based on sporocarps or mycelial isolations (Fujimura et al. 2008, Björbakmo et al. 2010, Fujiyoshi et al. 2011, Walker et al. 2011, Geml et al. 2012, Timling et al. 2012).

The history of lichenological exploration of the Arctic is long. Lichens are easy to collect and preserve, and samples were brought home even by early Arctic expeditions. Therefore, the distribution of lichens is reasonably well known, though crustose microlichens are underrepresented. The distribution of their associated lichenicolous fungi is much less known (Zhurbenko 2009a). The first major work was a lichen flora of Arctic Europe and Greenland (Fries 1860). Details of lichen exploration are reported in several checklists and floras (e.g. Lyne 1947, Krog 1968, Thomson 1979, 1984, 1990, 1997 for North America, Elvebakk & Hertel 1996 for Svalbard, Printzen 2008 for a summary). Greenland is represented by many floristic studies (e.g. Alstrup 1982, 2005, Alstrup et al. 2000, numerous papers by E.S. Hansen, as Hansen 2008, Hansen et al. 1987). Recently, a Panarctic Lichen Checklist including their associate lichenicolous fungi was compiled by Kristinsson et al. (2006, 2010). The exploration of Arctic lichenicolous fungi is reviewed by Zhurbenko (2010a). The diversity of lichenicolous fungi is relatively well known for Greenland, Svalbard and Russia (Alstrup & Hawskworth 1990, Alstrup & Elvebakk 1996, Zhurbenko & Santesson 1996, Lawrey & Diederich 2003, Alstrup 2005, Zhurbenko 2007, 2009a, 2009b, 2010a).

General characteristics of Arctic macrolichen11 communities have been summarized for lichen-rich vegetation in general (Ahti & Oksanen 1990), in Alaska (Holt et al. 2007), on rock in Greenland (Daniëls 1975) and for Arctic terricolous lichen communities (e.g. Nimis 1981, 1985, Daniëls 1982, Bültmann 2005, Bültmann & Daniëls 2009).

Lichens are established bioindicators for air purity (e.g. Nimis et al. 2002), but effects of air quality on species composition of Arctic lichen have not been reported. Lichens have been used as accumulation indicators for contaminants such as heavy metal cations, radionuclides, nitrogen, sulphur and organic compounds in the Arctic (e.g. Nash & Gries 1995, Walker et al. 2003).

Monitoring of fungi has not taken place in the Arctic. Two local monitoring studies in Greenland that include lichens show no trends for any aspect of lichen diversity as yet (Elberling et al. 2008 for 1997-2007 at Zackenberg, Daniëls et al. 2011 from 1968 to 2007 in Ammassalik). The site at Zackenberg is continuously monitored (Hansen 2006, Elberling et al. 2008), and monitoring

11 Macrolichens are defined as foliose (including squamulose) and fruticose lichens, which can mostly be identified macroscopically, while microlichens are crustose lichens, mostly visible to the naked eye, but require microscopic means to be identified.
Reindeer or caribou depend on lichens as winter food (e.g. Llano 1956, Inga 2007). Reindeer dig through the snow to feed on soil lichens. Most important are the reindeer lichens i.e. species of Cladonia, subgenus Cladina, and Stereocaulon spp. (see Box 10.1 Fig. 1). In boreal areas, reindeer also feed on lichens on tree trunks and twigs. Only older forests have enough epiphytic lichen biomass for food. Long-term studies showed a significant decrease of reindeer food lichens in Alaska (Joly et al. 2009). Higher winter temperatures caused by climate change will cause an increase in ice on top layers of snow by refreezing or rain making it more difficult for reindeer to dig out the lichens (e.g. Putkonen & Roe 2003 and Large Herbivore Network 2012). The ability of lichens, as of other fungi, to accumulate cations of heavy metals including radioactive elements is also problematic. Thus reindeer kept for human consumption should not graze in areas subjected to pollution with heavy metals. Especially in the sub-Arctic, the availability of and access to lichens for the reindeer of the indigenous peoples in the north of Eurasia is a complex and sometimes politically difficult topic. Some state-imposed reindeer management systems, such as the Paliskunta-system in Finland, have disrupted the traditional knowledgeable management of pastures, which has led to severe depletion of lichen in some areas (Mustonen et al. 2011).

**Box 10.1. Lichens and reindeer**

Reindeer or caribou depend on lichens as winter food (e.g. Llano 1956, Inga 2007). Reindeer dig through the snow to feed on soil lichens. Most important are the reindeer lichens i.e. species of Cladonia, subgenus Cladina, and Stereocaulon spp. (see Box 10.1 Fig. 1). In boreal areas, reindeer also feed on lichens on tree trunks and twigs. Only older forests have enough epiphytic lichen biomass for food. Long-term studies showed a significant decrease of reindeer food lichens in Alaska (Joly et al. 2009). Higher winter temperatures caused by climate change will cause an increase in ice on top layers of snow by refreezing or rain making it more difficult for reindeer to dig out the lichens (e.g. Putkonen & Roe 2003 and Large Herbivore Network 2012). The ability of lichens, as of other fungi, to accumulate cations of heavy metals including radioactive elements is also problematic. Thus reindeer kept for human consumption should not graze in areas subjected to pollution with heavy metals. Especially in the sub-Arctic, the availability of and access to lichens for the reindeer of the indigenous peoples in the north of Eurasia is a complex and sometimes politically difficult topic. Some state-imposed reindeer management systems, such as the Paliskunta-system in Finland, have disrupted the traditional knowledgeable management of pastures, which has led to severe depletion of lichen in some areas (Mustonen et al. 2011).

**Box 10.1 Figure 1.** Terricolous lichen vegetation is suitable for reindeer with reindeer lichens (here Cladonia mitis & C. rangiferina), Stereocaulon spp. and Flavocetraria cucullata. Photo: Helga Bültmann, Narsarsuaq, S Greenland.
results are published regularly in annual reports (e.g. Hansen 2006).

Wild mushrooms have rarely been used by indigenous Arctic peoples in the past (e.g. as hallucinogen: an *Amanita* species by Chukchi shamans (M.P. Zhurbenko unpubl.), *Amanita muscaria* and the shelf fungus *Polyporus sulphureus* in Yakutia (Jakutija 2007) and species of puffball for the treatment of wounds and cuts (Joamie et al. 2001, Cuerrier & the Elders of Kangiqsujuaq 2011). Only during the last decades have interest and use developed for edible mushrooms, for example in Chukotka due to Russian immigration (Yamin-Pasternak 2007).

In contrast, lichens have historically been used frequently as mild antibiotics (e.g. *Cetraria islandica* and the reindeer lichens) in medicine and food preserving, as food when half-digested in the stomachs of ruminants and, occasionally undigested, but mostly as famine food (e.g. ‘rock tripes’ *Umbilicaria spp.*), as dyes and as fuel or tinder or even soap (Llano 1956, Oswalt 1957, Richardson 1974, Sochting 1990, Joamie et al. 2001, Cuerrier & the Elders of Kangiqsujuaq 2011). A concise summary and bibliography of lichen use is compiled by Sharnoff et al. (2001, Cuerrier & the Elders of Kangiqsujuaq 2011). A concise summary and bibliography of lichen use is compiled by Sharnoff et al. (2001). Terricolous macrolichens are the main sources of food for reindeer and caribou with *Rangifer tarandus* (Box 10.1) constituting 70-75% of their annual diet, and periodically also used by other species including muskoxen *Ovibos moschatus*, lemmings (subfamily Arvicolinae) and hares *Lepus* spp. (Llano 1956). Even mushrooms such as bolete species of *Leccinum* contribute to the summer diet of reindeer (Knudsen 2001).

### 10.3. THE FUNGI OF THE ARCTIC

#### 10.3.1. Species richness

The total number of known fungal species in the Arctic is > 4,350 (Tab. 10.1). Of these, 1,750 are lichens and about 2,600 are fungi. Lichens consist almost exclusively of ascomycetes, while in fungi most are ascomycetes and 837 are basidiomycetes. About 2,030 of the fungal ascomycetes and basidiomycetes are macrofungi (non-systematic group), while the rest are microfungi consisting mainly of ascomycetes but also some Chytridiomycota, *Zygomycota* and *Glomeromycota* plus rusts and smuts (Tab. 10.2). 373 of the fungi have a lichenicolous life form.

These figures correspond to 4% of the globally known total number of fungi (> 99,000), but as much as 10% of the globally known lichens and > 20% of the globally known lichenicolous fungi (Tab. 10.1; Hawksworth 2001, Lawrey & Diederich 2003, Feuerer & Hawksworth 2007, Blackwell 2011). However, it has been estimated that more than 90% of the global fungal species remain to be discovered and described, and the current working estimate suggests that their number on the Earth is at least 700,000 and likely 1.5 million (Hawksworth 2001, Schmit & Mueller 2007). These authors suggest a general relation between numbers of species of fungi to vascular plants to be 5-8:1. The status of lichens is rather well known in contrast to that for fungi. Microfungi are particularly poorly investigated. In the Arctic, 2,218 vascular plant species have been recorded, which is roughly half as many species as for fungi (cf. Daniëls et al., Chapter 9). With a proportion of 6:1 of fungi:plants, the number of fungi would amount to ca. 13,000 fungal species in the Arctic.

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**Table 10.1.** Known and estimated total species richness of Arctic fungi.

<table>
<thead>
<tr>
<th>Fungal group</th>
<th>Taxonomic and functional group</th>
<th>Known total number of species</th>
<th>Estimated total number of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lichens</td>
<td></td>
<td>1,750</td>
<td>~1,750</td>
</tr>
<tr>
<td>Fungi</td>
<td></td>
<td>&gt;2,600</td>
<td>11,000</td>
</tr>
<tr>
<td>Chytridiomycota</td>
<td></td>
<td>83</td>
<td></td>
</tr>
<tr>
<td><em>Zygomycota</em></td>
<td></td>
<td>45</td>
<td></td>
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<tr>
<td><em>Glomeromycota</em></td>
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<td>Ascomycota</td>
<td></td>
<td>1,245</td>
<td></td>
</tr>
<tr>
<td>Basidiomycota</td>
<td></td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>Lichenicolous fungi</td>
<td></td>
<td>373</td>
<td>&gt;440</td>
</tr>
<tr>
<td>Non-lichenized macrofungi</td>
<td></td>
<td>2,030</td>
<td></td>
</tr>
<tr>
<td>Total number of Arctic fungi</td>
<td></td>
<td>&gt;4,350</td>
<td>&gt;13,000</td>
</tr>
</tbody>
</table>

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1) The mycobionts of lichens predominantly consist of ascomycetes, but here they are treated as a functional group and not included in the taxonomic groups (Appendix 10.1).
2) Svalbard and W Greenland are the two best known areas where macrolichens are considered to be completely sampled, constituting 31% and 37%, respectively, of the known number of lichen species, mean 34%. Macrolichens also constitute 34% of the known number of Arctic lichens, and thus we expect the total number of lichens in the Arctic not to be much higher than the known number.
3) Fungi refer to non-lichenised fungi.
4) Calculated from the highest number of known species for each fungal group in Greenland, Iceland, Svalbard or Arctic Russia.
5) Estimated from the suggested relationship between vascular plant and fungi 1.5(-1.7) (Hawksworth 2001, Schmit & Mueller 2007).
6) Lichenicolous fungi are predominantly ascomycetes, but are here treated as a functional group and not included in the taxonomic groups (Appendix 10.1).
8) Sum based on the species richness of macrofungi of *Ascomycota* (e.g. not anamorphic taxa) and *Basidiomycota* (cf. Tab. 10.2) and lichenicolous fungi.
<table>
<thead>
<tr>
<th>Fungal group</th>
<th>Iceland¹</th>
<th>Greenland²</th>
<th>Svalbard³</th>
<th>Arctic Russia⁴</th>
<th>Highest number used to infer known number of Arctic species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chytridiomycota</td>
<td>83</td>
<td>3</td>
<td>3</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Zygomycota</td>
<td>45</td>
<td>15</td>
<td>27</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Glomeromycota</td>
<td>11</td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Ascomycota</td>
<td>620</td>
<td>680</td>
<td>226</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Pyrenomycetes</td>
<td>(180)</td>
<td>(470)</td>
<td></td>
<td>470</td>
<td></td>
</tr>
<tr>
<td>Leotiales</td>
<td>(200)</td>
<td>(100)</td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Pezizales</td>
<td>(150)</td>
<td>(50)</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Anamorphic</td>
<td>425</td>
<td>200</td>
<td>103</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>Basidiomycota</td>
<td>716</td>
<td>837</td>
<td>201</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>Lichenicolous fungi⁵</td>
<td>14</td>
<td>231</td>
<td>75</td>
<td>140⁵</td>
<td>373⁶</td>
</tr>
<tr>
<td>Total number of known non-lichenized fungi</td>
<td>1,903</td>
<td>1,947</td>
<td>635</td>
<td>1,890</td>
<td>2,594</td>
</tr>
<tr>
<td>Known number of macrofungi</td>
<td>1,350</td>
<td>1,579</td>
<td>502</td>
<td>1,410</td>
<td>2,030</td>
</tr>
</tbody>
</table>

Lichenicolous fungi refers to low Arctic in Iceland, other fungal groups refer to all of Iceland (low and sub-Arctic).
3) Elvebakk & Prestrud 1996.
4) Karatygin et al. 1999.
5) Consists mainly of ascomycetes, but includes also basidiomycetes (Appendix 10.1).
6) Zhurbenko 2010a reports 250 species for the Russian Arctic, however including areas not corresponding with the Arctic as defined here (e.g. with Kola Peninsula).
7) Known Arctic species richness (Appendix 10.1).

Figure 10.1. Species richness of lichens in Arctic (a) sectors and (b) floristic provinces. Provinces are shown with different colors (n = 1,750). Continental species richness: North America 1,026, Greenland 1,136, Europe 1,075 and Asia 1,178.
10.3.2. Species richness in different geographical regions

The distributions of Arctic lichens and lichenicolous fungi are known in greater detail than those of other fungi (Fig. 10.1 and 10.2). The two best investigated areas concerning fungal diversity are Greenland and Svalbard with high documented species richness for fungi, lichens and their associated lichenicolous fungi (Tab. 10.2, Fig. 10.1 and 10.2). W Greenland is accessible from the coast and has been intensively studied historically and in recent years. It includes a small area with sub-Arctic birch forests in the very south, but only about 30 lichen species and 200 fungi are exclusively found in this sub-Arctic enclave (Jensen 2003). Svalbard is rather small and consists exclusively of high Arctic habitats. It has attracted many lichenological and mycological studies (e.g. Øvstedal et al. 2009, Bjorbækmo et al. 2010, Geml et al. 2012). No compilation of fungi is available from the main American Arctic, but a molecular study of ectomycorrhizal roots from 326 plants of Arctic willow Salix arctica and mountain avens Dryas octopetala collected along a gradient from the low to the high Arctic in north America identified 242 different ectomycorrhizal fungal species and no decline in species richness (Timling et al. 2012).

The difference in the number of recorded species among regions is due to several factors, including area size, the diversity and number of different habitats, and relative survey effort. The relatively lower species richness in many of the vast Arctic areas in North America and Russia, for example, is probably caused by fewer surveys having been conducted there.

![Figure 10.2. Species richness of lichenicolous fungi in Arctic floristic provinces. Species richness in Arctic sectors: Beringia 157, Canada 89, North Atlantic 256, European Russia & western Siberia 90 and eastern Siberia 176 (see Fig. 10.1 for delimitation). Continental species richness: North America 80, Greenland 231, Europe 111 and Asia 243.](image)

<table>
<thead>
<tr>
<th>Regions</th>
<th>All substrates</th>
<th>Bark</th>
<th>Wood</th>
<th>Soil</th>
<th>Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Arctic</td>
<td>1,230</td>
<td>101</td>
<td>33</td>
<td>358</td>
<td>738</td>
</tr>
<tr>
<td>Low Arctic</td>
<td>1,450</td>
<td>215</td>
<td>53</td>
<td>413</td>
<td>769</td>
</tr>
<tr>
<td>Sub-Arctic Greenland</td>
<td>671</td>
<td>88</td>
<td>25</td>
<td>211</td>
<td>347</td>
</tr>
</tbody>
</table>

Exclusively sub-Arctic Greenland: 32 species, low Arctic: 432 species; high Arctic: 204, in low & high Arctic: 1,018 species, sub- & high Arctic: 8 species.

10.3.3. Distribution of species within different Arctic zones

Knowledge of the distribution of fungal species in the low and the high Arctic, respectively, is fragmentary and has not yet been compiled and analyzed. However, these species are largely dependent on the occurrence and abundance of plants, and hence their distribution may be inferred from the distribution of plants. Plant species richness and abundance decline from the low to the high Arctic, which support 2,183 and 111 species of vascular plants, respectively (Daniëls et al., Chapter 9). The occurrence of specific plant species determines which species may be present, and different plant species are associated with different numbers of fungi. High Arctic root-associated fungal communities are reported to be quite distinct for six plant species (Fujimura & Egger 2012). In contrast, the two principal ectomycorrhizal Arctic plants, mountain avens and arctic willow, form ectomycorrhizae with more than 250 fungal species that they largely share (Bjorbækmo et al. 2010, Timling et al. 2012).

The distribution of Arctic lichens is better known than that of fungal species. Almost 60% of the lichen species occur in both the low and the high Arctic (Tab. 10.3). On average, lichen species richness declines by 15% from low to high Arctic in contrast to species richness in vascular plants, which declines by 95% (Tab. 10.3; Daniëls et al., Chapter 9). Most of the decline in lichens is among species growing on bark and wood and there is some decline among species growing on soil and rocks. In some high Arctic areas, e.g. in Canada and Svalbard, lichen species richness can be higher than in the low Arctic (Appendix 10.2).

Arctic fungal diversity hotspots on a landscape scale are not known, but compared with the low plant diversity in Arctic communities, the species richness and heterogeneity of lichen communities is high (e.g. Lünterbusch & Daniëls 2004, Bültmann 2005, Bjorbækmo et al. 2010, Geml et al. 2012, Timling et al. 2012), as high as in species-rich communities outside the Arctic such as calcareous grasslands (Bültmann 2011).
Species richness of 700 lichens and of 100 lichenicolous fungi is documented for hotspots in mountain areas in the boreal zone, adjacent to Arctic areas (Elvebakk & Bjerke 2006: 709 lichens, 94 lichenicolous fungi in Norway, and Spribille et al. 2010: 668 lichens, 98 lichenicolous fungi in Alaska). Species richness in potential Arctic hotspots could be expected to be slightly lower because of the decline in the number of epiphytic lichens. However, small-scale diversity in vegetation study plots in the Arctic has been shown to be very high, in most cases due to a large number of lichens; up to 50 species on less than 1 m² (Tab. 10.4). For soil fungi, a molecular study detected 332 fungal taxa in 600 soil cores in Svalbard (Geml et al. 2012).

### 10.3.4. Distribution of different life forms and at different substrates

The most well-known fungal life form in the Arctic is lichens, comprising 40% of the known species, while ectomycorrhizal fungi constitute at least 6% and lichenicolous fungi about 9% of known species. The remaining known species are predominantly saprotrophic, the majority litter- and soil-dwelling with a few wood-inhabiting species, and only a few are parasitic species (e.g. rust and smuts). Most Arctic lichen species are rock dwellers (56%), followed by lichens on soil (26%), bark (14%) and wood (4%; Appendix 10.2). The proportions of lichen species growing on these substrates are similar in boreal and temperate biomes, except for the proportion of ‘bark’ species which is higher there, about 30% (Bültmann 2010). In the Arctic, as in the other biomes, a larger portion of lichen species grows on acidic substrates rather than on calcareous substrates (Appendix 10.2; see also Bültmann 2010). Most species of lichenicolous fungi are found on lichens with soil or plant debris as substrate (for the Russian Arctic: 63%; Zhurbenko 2010a). Fewer are associated with rock-dweller (33%) and bark/wood-dweller species (4%). Most Arctic lichens (66%) are crustose, i.e. microlichens, while 34% are macrolichens (7% of squamulose, 13% of leaf-like (foliose) and 14% of small-shrubby (fruticose); Appendix 10.2).

### 10.3.5. Specificity to the Arctic and rarity

Few species if any, of fungi are exclusively confined to the Arctic. The potential degree of endemism is probably less than 2% in fungi (H. Knudsen pers. com.). Some genera and several species are predominately Arctic-alpine circumpolar in their distribution, while the remaining species also may occur in boreal and temperate habitats (Gulden & Torkelsen 1996, Knudsen 2006). The distribution of 422 circumpolar Arctic microfungi was reported and discussed by Lind (1927). More recently, circumpolar distribution has been examined and reported for a few species of Arctic macrofungi (Knudsen & Mukhin 1998, Cripps & Horak 2006, Cripps et al. 2010, Ronkier & Ronkier 2010, E. Larsson pers. com.). DNA sequence analyses of the identity of Arctic ectomycorrhizal fungi in mycorrhizal host roots imply that many may be distributed globally and are found also in boreal, temperate and Mediterranean biomes (Geml et al. 2012, Timling et al. 2012).
The majority of Arctic lichen species have more limited distributions. About 25% are known from the entire Arctic, a further 25% from three or four sectors (delimitations of sectors see Fig. 10.1), while 49% are known from only one or two sectors. This is a wider distribution than reported for vascular plants, for which about 70% of the taxa are found in one or two sectors and 10% in all five (Elven 2007 onwards). The lichen species known only from one geographic region are mostly very rare in the Arctic. Overall, 48% of the Arctic lichens are classified as very rare in the Arctic (Appendix 10.2). The majority of those (64%) are common or scattered outside the Arctic (Fig. 10.3).

At the moment, 143 lichen species are listed as Arctic endemics (Appendix 10.1). Five of these are widely distributed within the Arctic while the majority is classified as very rare (Appendix 10.1 and 10.2). These Arctic endemics are mainly rock-dwelling microlichens occurring in the high Arctic (Tab. 10.5). However, a taxonomic revision is needed for many of these lichens in order to settle their taxonomic status (Kristinsson et al. 2010). A recent critical reexamination of 52 rare lichen taxa reported in Norway concluded that only 30% of them were appropriately identified to the species level and that the remaining were probably synonyms to more common species (Jørgensen & Nordin 2009).

Most lichens with scattered or common distribution in the Arctic are also scattered or common outside the Arctic (Fig. 10.3). The 215 Arctic lichen species that are rare outside the Arctic are predominantly rock-dwelling crustose microlichens (Tab. 10.5).

### 10.4. TRENDS, CAUSES AND PROSPECTS

Arctic climate and vegetation, including fungal communities, have undergone major changes during past glacial and interglacial periods (Lydolph et al. 2005; de Vernal & Hillaire-Marcel 2008). Fungal species have repeatedly disappeared and re-colonized the present Arctic, the fungi following their associated plants, and the lichens responding to availability of suitable habitats. There is growing evidence that the advance of flowering plant vegetation is speeding up as is the ‘greening’ of Arctic tundra, similar to related changes occurring in mid-latitude alpine regions (Wookey et al. 2009; see also Ims & Ehrich, Chapter 12). Altered vegetation drives fungal communities to change. Increasing productivity and increasing biomass in the low and the high Arctic – including increasing shrub cover in the low Arctic – will result in increased fungal activity and biomass, alter composition of fungal communities and may subsequently affect fungal ecosystem processes (e.g. Wallenstein et al. 2007, Deslippe et al. 2011). These changes will mainly be a response to altered composition of plants and increased photosynthesis levels, but other biotic and abiotic factors may also play roles.

It is obvious that the occurrence and abundance of fungi will track those of their associated plants, but so far the fungal consequences of climatically induced vegetation changes have only been studied to a limited extent (Pickles et al. 2012, Timling & Tayler 2012). One of the few studies of vegetational changes and fungal diversity reports large effects on the composition and functions of ectomycorrhizal fungi in an 18-year long-term experimental greenhouse warming of dwarf birch *Betula nana* (Deslippe et al. 2011). This experiment resulted in higher mycelia biomass in ectomycorrhizal fungi characterized by mycelia of long distance exploration types and capacity to mobilize organic nitrogen (e.g. in webcaps *Cortinarius* spp.). At the same time, there was a reduction of fungi with mycelia of the contact exploration type, like brittle gills *Russula* spp.; these have an affinity to labile inorganic nitrogen. The authors infer that warming may profoundly enhance decomposition of soil organic matter and increase the connectivity of dwarf birch through mycorrhizal networks of larger size. These changes may further facilitate shrub expansion by enhancing nitrogen acquisition and nutrient redistribution to dwarf birch. The reports of earlier spring and later autumn fruiting behavior of macrofungi in Europe due to current climatic warming (Kaiserud et al. 2008, 2010, 2012) reflect increased fungal activities below ground; such changes are also likely to take place in the Arctic.

The predicted profound influence of increased average air temperature and annual average precipitation in the Arctic will have effects on ecosystem functions that are difficult to predict (ACIA 2005). The effects on global carbon cycling and atmospheric CO$_2$ levels will significantly depend on how the diversity and functions of

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>High</th>
<th>Only low</th>
<th>Only high</th>
<th>Only in 1 sector</th>
<th>Only in 1 province</th>
<th>Microlichens</th>
<th>Macrolichens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endemic</td>
<td>83</td>
<td>103</td>
<td>36</td>
<td>56</td>
<td>84</td>
<td>72</td>
<td>125</td>
<td>18</td>
</tr>
<tr>
<td>Rare</td>
<td>152</td>
<td>138</td>
<td>41</td>
<td>48</td>
<td>98</td>
<td>80</td>
<td>174</td>
<td>41</td>
</tr>
</tbody>
</table>

Microlichens: crustose, Macrolichens: squamulose, foliose and fruticose
fungal communities are affected due to their key roles in terrestrial carbon cycling (e.g. Ludley & Robinson 2008, Pickles et al. 2012). The uncertainty of how the large Arctic soil pool of carbon will change with changing vegetation, soil temperature and permafrost will also depend on (1) how vegetation patterns will change and feed back to climate, (2) how diversity of fungal and bacterial communities will change in relation to vegetation change, and (3) how the subsequent fungal and bacterial carbon-cycling processes will be affected. It has recently been reported that a major portion of stored carbon in boreal forests derives from roots and root-associated microorganisms, probably with ectomycorrhizal fungi as key-players (Clemmensen et al. 2013). As fungi similarly may be important for the carbon flux in Arctic soils, changing vegetation and fungal communities may affect the amount of stored carbon. Yet, the abundance, diversity, functions and potential reactions to climate change of fungi in the Arctic are not well understood.

Lichens are autotrophic and less dependent on vascular plants, though some may compete with plants and some grow on bark. The majority of lichen species, including most endemic and rare species, grows on rock surfaces and do not compete with vascular plants. Nevertheless, changes in temperature and moisture regime will gradually cause changes in the species composition of lichen communities. The Arctic epiphytic lichens may be favored by the spreading of shrubs and trees to the north, while terricolous lichens can be expected to face increasing competition from vascular plants.

The recently established local long-term monitoring of lichen communities at Greenland has not detected any effects of climate change. In the Netherlands, long-term monitoring of lichen communities has revealed changes that are suggested to be partly due to warming since 1990 with a rather rapid increase in some and a decrease in other species (van Herk et al. 2002, Aptroot 2009). However, these findings are only partly applicable to the Arctic. In the Netherlands, the increase in (sub-)tropical species concerns mainly species recovering from the losses by former SO2-pollution, and the decrease in boreo-montane/Arctic-alpine species concerns mainly terricolous species suffering from changes in land management of semi-natural grassland and heath-land and is fuelled by anthropogenic emissions of nitrogen compounds (primarily NO3 and NH3; e.g. Hauck 2009).

Increasing nitrogen input to ecosystems has large direct and indirect effects on species diversity of both ectomycorrhizal fungi (e.g. Lilleskov et al. 2002) and lichens. Atmospheric nitrogen deposition in the Arctic is expected to increase in the future (Callaghan 2005). Such input of nitrogen will increase vascular plant growth and competition with a negative effect for the Arctic terricolous lichen, including the lichens essential as reindeer food. Field experiments document that increased vascular plant vegetation results in a decline in soil-inhabiting macrolichen abundance in the sub- and low Arctic, including reindeer food lichens (Joly et al. 2009), but this is not yet apparent in the high Arctic (Cornelissen et al. 2001).

It is possible to infer potential future distribution of fungi by combining predicted changes in habitat types or vegetation cover in the Arctic with their ecology. Hence, it would be feasible to initiate monitoring programs for any of these fungal groups. Lichens would best be monitored through visual surveys (e.g. Elberling et al. 2008) and fungi through a combination of sporocarp observations and molecular analyses of environmental samples. Recent advances in molecular methods, e.g. pyrosequencing, efficient bioinformatics and increasing sizes of databases of fungal reference sequences are promising in this regard (e.g. Buée 2009, Geml et al. 2012, Timling et al. 2012). Soil animals are increasingly being monitored using such methods (Heger et al. 2012).

The conservation status of macrofungi and lichens has not been evaluated for any fungal group at the circum-polar level, for Arctic-alpine environments or at the global level (IUCN 2012). None of the three globally ad hoc red-listed fungal species (two lichens and one fungal species) occurs in the Arctic (IUCN 2012). Given the relatively large distributional and ecological knowledge of Arctic lichens (Kristinsson et al. 2010), a red-list evaluation and the conservation status of Arctic lichens could be established. It is a challenge that many rare lichens are known only from ancient collections. The evaluation of conservation status should include detailed information about the distribution of rare and endemic Arctic lichens to avoid unintentional destruction of rare lichens by e.g. construction works, such as reported by Thomson (1997) as a possibility for a type locality in Alaska. Similarly, the conservation status of Arctic macrofungi, although based on substantially less knowledge, may for a large share of the species be evaluated based on published and anecdotal knowledge in combination with data on habitat trends (Dahlberg & Mueller 2011).

Field surveys, monitoring programs and research are needed to maintain and develop knowledge of Arctic fungi. However, today’s knowledge of Arctic fungi relies on a very small number of experienced and skilled people. There is a general concern that universities and government agencies rarely hire field-experienced scientists with a broad taxonomic knowledge. This is particularly true for Arctic fungal specialists. Without opportunities for such positions, Arctic fungal biodiversity will attract little attention and loss of fungal diversity may go unnoticed and undocumented resulting in causes for changing fungal-dependent ecosystem processes be less understood.

10.5. CONCLUSIONS AND RECOMMENDATIONS

Fungi is a key group of organisms with high species richness and large significance for ecosystem processes in the
Arctic. Except for macrolichens, however, their presence and significance has often been overlooked and poorly appreciated in the Arctic, despite being species rich, abundant and pivotal in carbon and nutrient cycling. Distributional and ecological knowledge is reasonably good for macrolichens but sparser for fungi and microlichens.

Even with these caveats, present knowledge largely enables us to predict the future of Arctic fungi. The unavoidable greening of the Arctic will steadily and significantly affect the distribution and abundance of fungi, as habitat conditions gradually transform the distribution and abundance of plants. This change is in progress already, but studies of Arctic soil fungal communities imply that the response as yet is relatively slow (Timling & Taylor 2012). Therefore, we judge that these changes will only rarely affect their conservation status in the immediate future. However, over time the effects of climate change and subsequently transformed vegetation will have profound effects on the distribution and composition of fungi and consequently also their ecosystem functions. Most of the species are circumpolar and also distributed outside the Arctic. However, a large proportion of them are confined to Arctic-alpine habitats of which the greater part is located within the Arctic and few are true Arctic endemics.

The following actions would enable a more thorough analysis of the status and trends of Arctic fungi.

- Long-term funding is necessary to maintain and train Arctic specialists in mycology and lichenology and to ensure research and monitoring to take place.
- The identity and taxonomy of species with unclear status (e.g. poorly known fungi and potentially endemic lichens) should be critically examined. The large potential of fungal analysis of deep sequenced environmental samples will largely benefit by clarified fungal taxonomy.
- A check-list for Arctic fungi should be compiled.
- The knowledge of distribution and ecology for all fungi, but in particularly for non-lichenized fungi, should be improved.
- Conservation status should be assessed for Arctic lichens and fungi, preferentially at both the Arctic and global scales.
- Long-term monitoring within representative Arctic habitats would enable us to document and follow fungal species shifts over time.
- Analyses of how vegetation changes may, based on knowledge of fungal ecology, predict potential habitats for fungi in space and time.
- Efforts to analyze the effects of slowly shifting fungal communities on ecosystem processes such as nutrient cycling and carbon fluxes are needed.
- Analyses of how the supply of reindeer food lichen communities will alter due to vegetation change should be conducted in order to better predict future conditions for populations of reindeer/caribou.

ACKNOWLEDGEMENTS

We gratefully acknowledge Henning Knudsen for suggestions and providing data from Greenland, Greg Mueller for contributing to the estimate of the potential number of Arctic fungal species, and Ellen Larsson, Sveta Yamin-Pasternak, Tero Mustonen and Violet Ford for other information. The work was partly sponsored by the Swedish Environmental Protection Board.

REFERENCES


and cascade processes: understanding their role in the responses of Arctic and alpine ecosystems to environmental change. Global Change Biology 15: 1153-1172.


Zhurbenko, M.P. 2010b. Lichenicolous fungi and lichens growing on Stereocaulon from the Holarctic, with a key to the known species. Opuscula Philolichenum 8: 9-39.

Zhurbenko, M. 2012. Lichenicolous fungi growing on Thamnolia, mainly from the Holarctic, with a worldwide key to the known species. Lichenologist 44: 147-177.


Appendix 10: www.abds.is/aba-2013-appendix-10